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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

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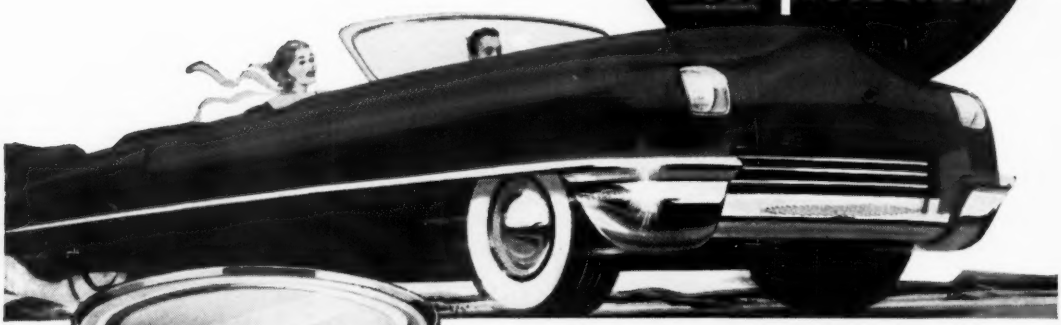

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LUBRICATION

A TECHNICAL PUBLICATION DEVOTED TO THE SELECTION AND USE OF LUBRICANTS

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VISCOSITY

AT VARIOUS times in the past, we have published articles dealing with viscosity, its measurement and significance. Inasmuch as this is probably the most important of all physical properties of a lubricant, this article has been prepared as a collection and amplification of information on this subject for reference as well as for current reading.

It is probably desirable to start this article with a few definitions: *Viscosity* in general is the manifestation of friction between the molecules of any fluid. As here defined, a *fluid* may be either a gas or a liquid. If the former, the molecules tend to repel each other and the gas will expand so as to completely fill any enclosing vessel. A *liquid*, on the other hand, will flow so as to adapt its shape to any containing vessel, but without appreciable change of volume by pressure. The rate at which either gas or liquid accommodates itself to a change in shape is influenced by its viscosity, or the friction between its molecules. All fluids, liquid and gaseous, have the common characteristic of yielding to any force no matter how small. The rate they yield, or flow is controlled by this viscosity.

While viscosity is a property of all fluids, it is generally noticeable only when pronounced, such as in lubricants and in liquids referred to in the dictionary definition of this word as "thick, glutinous, sticky," etc. The word *viscosity* comes from the botanical word *viscum* for mistletoe, and refers to the viscous sticky fluid exuded by this plant.

Viscosity impedes the flow of all fluids, and is therefore of interest to those concerned with the rate of flow of fluids in pipes, through orifices, in bearings, etc. The specific application of laws of viscous flow will become evident as this discussion expands.

THE viscosity of lubricating oils is of such vital importance to the manufacturers and users of lubricants that they may be tempted to overlook those phases of the whole general picture of viscosity as it applies to other fields and other industries. The purpose of this article is not only to describe viscosity of lubricants, but to show how it fits into the larger general picture. It is believed that this may give a more thorough concept of the subject.

Of the six parts into which this article is divided, the first illustrates the simplest concept of streamline flow between two surfaces having relative motion. A series of torsion viscometers is illustrated to show how viscosity acts and may be measured in this type of fluid flow. Part II covers streamline flow in capillary and other small tubes. This includes the efflux viscometers which are so commonly used in the petroleum industry. Part III covers turbulent flow as usually encountered in pipes, Part IV goes into some detail on the effects of temperature and pressure on viscosity, and Part V includes Viscosity Index. A very brief reference to the nature of plastic flow is given in Part VI.

PART I

STREAMLINE FLOW BETWEEN SURFACES HAVING RELATIVE MOTION

The classic illustration which is generally used to explain this property is that shown in Figure 1, which represents two plane surfaces having relative motion, and separated by a fluid which "wets" both.

The movement of the fluid during so-called "streamline" flow, when all particles move in parallel planes, progresses uniformly between successive imaginary layers of the liquid, so that the "rate of shear"* is uniform between all layers. In this type of motion, the force required to overcome the internal friction of the fluid, when one of the planes is moved at a given velocity and at a known distance from the other, varies directly with the viscosity of the fluid, the rate of shear, and the area of the plane surfaces. Obviously, the magnitude of this force may be used as a measure of the viscosity when all dimensions are fixed. In this way, the fundamental unit of viscosity has been defined as the viscosity which requires one unit of force to move a surface of unit area at unit velocity when spaced one unit from a stationary plate, all dimensions being metric (C.G.S.). This unit of viscosity was named a Poise in honor of Dr. J. L. M. Poiseuille, who, as a physician, about one hundred years ago made an extraordinarily thorough study of the flow of liquids in very small glass capillaries[1] as an approach to a study of the flow of blood in human capillaries. It is an interesting sidelight that had Poiseuille used blood in his experiments, he would probably have failed in laying down these fundamental laws for the flow of fluids, since blood does not obey the laws of true fluids.

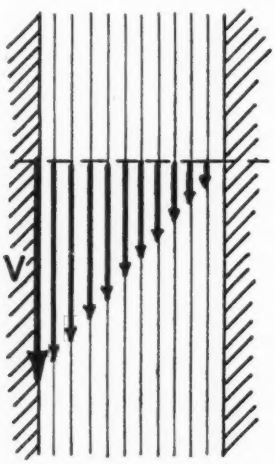
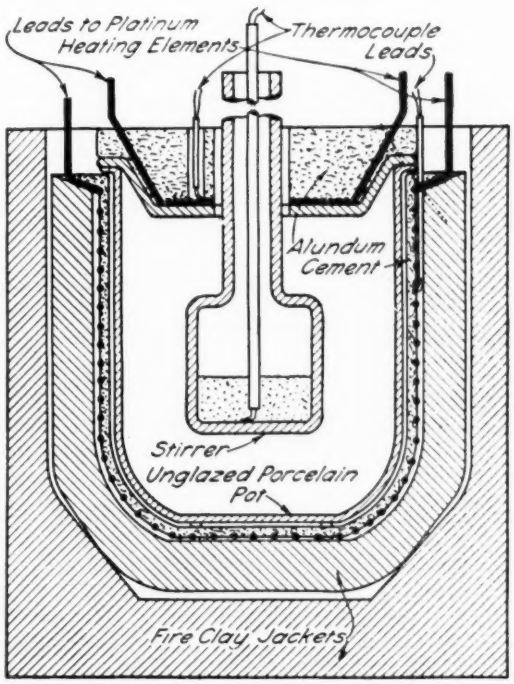


Figure 1 — Schematic streamline flow of a fluid between two surfaces having relative velocity "V". Velocities of successive layers are proportional to distance from the fixed surface.

*See equation (3).



Courtesy University of Illinois' Bulletin No. 140, Page 14, Engineer Experimental Station 1924

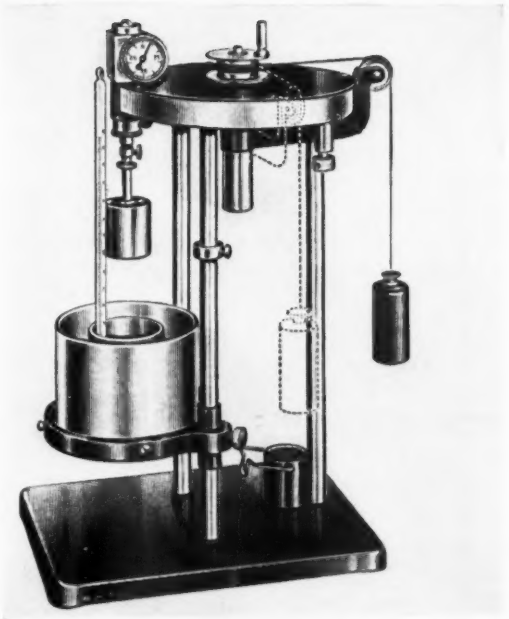
Figure 2 — Details of Viscometer for measuring of viscosity of molten glass.

In practice the Poise is so large a unit that in most applications in the oil industry, the values for oils would be much smaller than unity. For this reason it is customary to use a unit one-hundredth as large, called a *centipoise*. Thus the viscosity of water which is 0.01 poises at 68.4°F., is 1.00 cp (centipoise). The centipoise scale may therefore be looked upon as expressing viscosities in terms of the viscosity of water at 68.4°F. An oil of 10 cp viscosity is therefore ten times as viscous as water at 68.4°F.

Torsion Viscometers

A practical application of the fundamental arrangement shown in Figure 1, of a surface moving parallel to another, is that of a cylinder rotating at the center of a cylindrical vessel containing a

[1] "A Monograph of Viscometry", Guy Barr, p. 9; also: "Fluidity and Plasticity", E. C. Bingham, p. 330.



Courtesy of Eimer and Amend

Figure 3 — Stormer Viscometer, used to some extent for asphalts and similar liquids. The cylindrical element is rotated by the weight at the right. The cup containing the sample is shown lowered for cleaning. In use the cup is raised until the rotor is submerged. A water bath surrounding the cup aids in maintaining constant temperature. Readings are taken of the time required for 100 revolutions of the cylinder as indicated by the revolution counter above the cylinder.

fluid. Newton[2] made a basic theoretical study of the effect of viscosity on the force required to rotate such a cylinder more than 200 years ago. He then showed that the force required was directly proportional to the viscosity and rate of shear (which increases directly with the rotational velocity). This is the basis of the class of instruments devised for measuring viscosity known as torsional viscometers. They have been used considerably in the chemical industry, an example being the measurement of the viscosity of molten glass,[3] and even of blast furnace slag at temperatures up to 3000°F.[4] Figure 2 shows such a viscometer for molten glass, in which the viscosity is measured by the force required to rotate the cylindrical porcelain "stirrer". With proportionately smaller clearance space, this will be recognized as being similar to a concentric oil lubricated bearing, such as may be found on a vertical shaft. Equations are available[5] by which the viscosity of a fluid may be calculated from the dimensions of such an instrument and the rate of turning the cylinder, but it is more usual and simpler to calibrate with fluids of known viscosity. For instance, castor oil at room temperature was used to calibrate the viscometer previously referred to which was designed for blast furnace slag at very high temperatures. In this calibration the following type of equation is used:

$$(\text{viscosity}) = K \frac{(\text{Force causing rotation})}{\text{RPM}} \quad \ldots (1)$$

Calibration consists merely of determining the value of K in this equation for a given instrument with a fluid of known viscosity. In the interest of greater accuracy the constant K would normally be determined over a range of viscosities and temperatures, to assure that no extraneous variables are

Courtesy of Eimer and Amend

Figure 4 — MacMichael Viscometer. The cup containing the oil sample is rotated by a motor at constant speed, and readings are taken of the Torsional Deflection of a wire which supports a stationary cylinder immersed in the oil.

[2] "Viscosity of Liquids", Hatschek p. 1.
[3] Univ. of Ill. Bull. #140, Eng. Exp. Station (1924).
[4] Dept. of the Interior (Bureau of Mines) Tech. Paper 157.

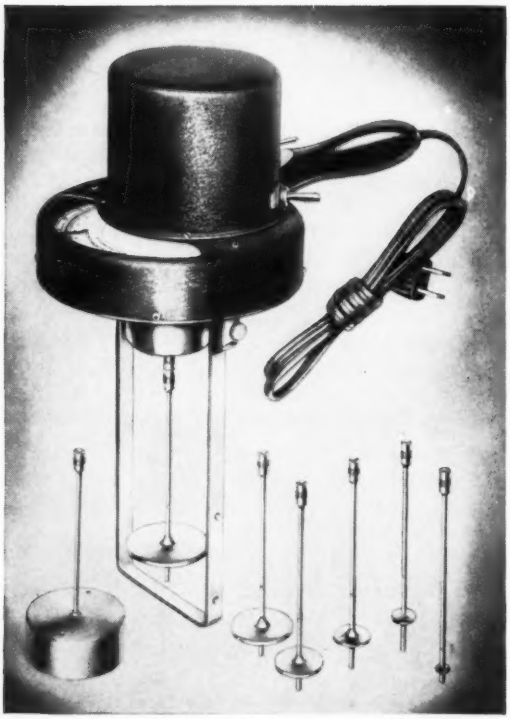
[5] $\text{Torque} = \frac{5.55\ (\text{Shear rate})\ (\text{Viscosity}) \times abh}{10^8}$ ... (2)†

where: a = radius of rotating cylinder in cm
b = radius of stationary cup in cm
h = height of cylinder in cm
Viscosity is in centipoises,
Torque is in inch-pounds, and

$$\text{Shear rate} = \frac{2\pi\ \text{rps}\ (\text{Effective radius})}{(\text{film thickness})} = \frac{4\pi\ ab.\text{rps}}{(b^2 - a^2)} \quad \ldots (3)$$

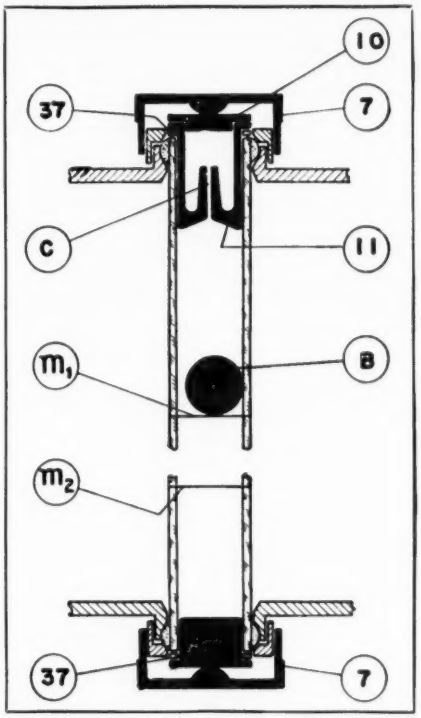
where: $\text{Effective radius} = \frac{2ab}{b+a}$

†See: Barr, p. 222.



Courtesy of Brookfield Engineering Laboratories, Inc.

Figure 5 — Brookfield Viscometer. Several types of rotor spindles including cylinders and disks, may be rotated in a beaker of oil by a Synchronous Motor. Several speeds are provided by a gear shift. A scale indicates the torque transmitted to the spindle as a measure of viscosity.



Courtesy of Fish-Schurman Corp.

Figure 6 — Höppler Falling Ball Viscometer. A steel or glass ball is inserted in the glass tube shown, which is then filled with the fluid to be tested. The tube is assembled in a larger glass cylinder which acts as a constant temperature bath. The whole assembly is arranged to be inverted and the time measured for the ball to cross the two calibration lines m_1 and m_2. Selection of balls with various clearances and densities permits a range of viscosities from air to cylinder oil.

introduced in the range over which it is to be used.

Examples of the above instrument are the Stormer, shown in Figure 3, and the MacMichael shown in Figure 4, which are used occasionally in the petroleum industry for very viscous liquids. Another example shown in Figure 5 is used in the paint industry, where viscosity is measured as torque required to rotate a cylinder or disk at fixed speed in a beaker of the test fluid. A somewhat similar torsional viscometer developed by The Texas Company is used for measuring the viscosity of mud suspensions used in oil well drilling operations.

Other examples of the dependence of viscosity on force-velocity relations between surfaces having relative motion and encompassing a fluid include the damping rate of a submerged pendulum and the rate of fall of a ball of known size and weight.[6] Similar laws cover the rate of fall of rain drops,

---

[6]For a sphere falling in a viscous medium: Stokes Law:*

$$(\text{velocity}) = 21800 \frac{(\text{difference in densities})}{(\text{viscosity})} \times (\text{radius of sphere})^2 \quad \ldots (4)$$

This holds only for low Reynolds Numbers.

For a sphere falling through a fluid along the axis of a tube:†

$$(\text{viscosity}) = 21800 \frac{(\text{Radius of Sphere})^2 \times (\text{difference in densities})}{(\text{velocity in cm/sec})\left(1 + 2.4 \frac{\text{sphere radius}}{\text{tube radius}}\right)\left(1 + 3.3 \frac{\text{sphere radius}}{\text{height of liquid}}\right)} \quad \ldots (5)$$

All dimensions above are in cm, time is in seconds, and viscosity is in cp.

*Hatschek: "Viscosity of Liquids", p. 34.
Barr: "A Monograph of Viscometry", Chapter VIII.

†From University of Illinois Bull. #140, p. 20.

and even fog particles. The rate of fall of a ball of known weight has been used as a means of measuring viscosities under special conditions, such as where very high pressures or temperatures exist. Figure 6 shows the essential parts of a laboratory type instrument devised on this principle.

Typical torsional instruments generally combine both advantages and disadvantages, such as the relatively large volume of fluid required, and the fact that they may supply continuous readings of a stream of fluid during manufacturing processes. The large volume tends to minimize errors that might result from stratification of colloidal or non-homogenous mixtures of materials such as occur in molten glass, paint, etc. Where there is considerable space between the moving and stationary elements, small inaccuracies in the dimensions of either are generally not serious. In routine testing of liquid petroleum products, the volume required and the complication of moving mechanical parts are both undesirable, so that torsion viscometers are not customarily used in this service.

PART II

STREAMLINE FLOW IN SMALL TUBES – EFFLUX VISCOMETERS

For measuring the viscosity of homogenous fluids such as oils, fluid flow by gravity through a capillary tube is one of the simplest methods, and can be accomplished with small samples of fluid.

For a fluid flowing through a capillary tube similar reasoning to the laminar flow between two plates, visualizes a series of concentric tubes of fluid moving past each other at velocities increasing with the distance from the wall of the enclosing tube as indicated in Figure 7. This type of flow was summarized by Poiseuille in the following equation

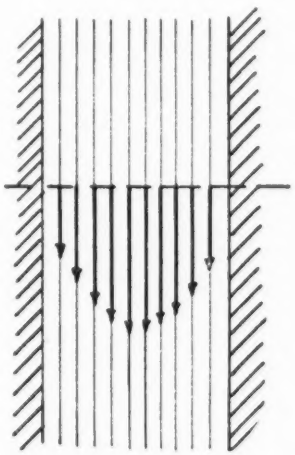


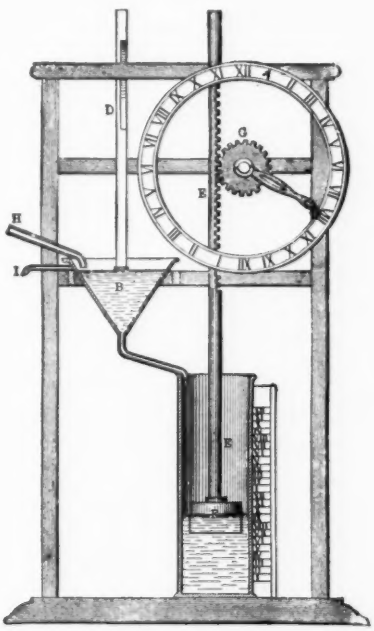
Figure 7 – Schematic streamline flow of a fluid in a tube. Concentric tubular sections have increasing velocities from the tube wall to the center.

which is frequently referred to as Poiseuille's Law:

$$\left\{\begin{matrix}\text{volume}\\ \text{discharged}\\ \text{per second}\end{matrix}\right\} = \frac{(\text{tube diameter})^4 \times (\text{pressure})}{(\text{tube length}) \times K} \quad . . (6)$$

The constant K in this equation incorporates the viscosity and the dimension units used. Note the large influence of small changes or errors in measurement of the diameter.

Observation of the time of flow of a fluid through any capillary tube may thus become a measure of its viscosity. The converse is true also; the rate of flow of a fluid of known viscosity may be used as a measure of time. While we have more satisfactory



Courtesy of The Macmillan Company
Reprinted from book by Dr. Willis I. Milham entitled "Time and Timekeepers"
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Figure 8 – A Clepsydra or Water Clock used in ancient Greek and Roman times. It is really an "Inverted" Efflux Viscometer in which the flow of water from a constant level source measures time, instead of time being measured to determine viscosity.

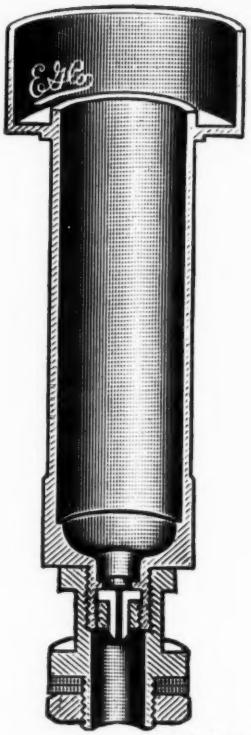
means of measuring time nowadays, it should not be overlooked that this principle of an "inverted viscometer" was used quite generally by the ancients to measure time. It was the principle of the "Clepsydra" or water clocks such as shown in Figure 8, which were used in India and China about 2000 years ago, and in turn were believed to have originated in Babylonia or Egypt.

Poiseuille's simple equation was later expanded to account for the effects of individual dimensions,[7] in a form applicable to any case where a fluid flows by gravity and the rate of flow is determined by measuring the time required for the flow of a given volume. This may be expressed in the simpler form:

$$\frac{\text{abs. vis.}}{\text{density}} = A\ (\text{efflux time}) - \frac{B}{\text{efflux time}} \quad . . (11)$$

in which time of flow is in seconds. The constants A and B apply to dimensions which are fixed for any one piece of apparatus and may be determined experimentally by testing with two or more fluids of different but known viscosities. Notice that if the time factor is large enough, the second term may be small enough to be neglected.

In all apparatus where oil flow is caused by gravity, and in many other applications of formulae relating to viscosity, the ratio of viscosity to density generally occurs. This ratio is called *kinematic viscosity*. It is used so frequently that a characteristic unit has been defined as the *Stoke*, which is the ratio of viscosity in Poises, to the density at the same temperature. The *Centistoke* (abbreviated: cs) which corresponds to Centipoises, is coming into general use in the petroleum industry.



Courtesy The Emil Greiner Co.

Figure 9 — The Commercial Saybolt Viscometer Tube shown in section.

Commercial Viscometers

In commercial viscometry of lubricating oils, several efflux type viscometers which are somewhat similar to each other have been in general use for many years; Redwood in England, Engler in Germany, Barbey in France, and Saybolt in the United States. With the exception of the Barbey, these are all very similar except in various dimensions and have the distinction of using relatively short capillary orifices. A description of the Saybolt will suffice for them all. Figure 9 shows a section of a Saybolt viscometer tube, and Figure 10, a water bath in which it is usually assembled. The tube is made of brass, and when filled, holds about 70 cc of oil above the orifice.† Viscosity readings with this instrument are reported in terms of the time of flow in seconds, of 60 cc of oil. Uniformity of production instruments is obtained by close manufacturing tolerances

[7]When flow is by pressure.*

$$\frac{\text{Poises}}{\text{Density}} = \frac{\pi g r^4 t P}{8\rho V(L+\lambda)} - \frac{m V}{8\pi t(L+\lambda)} \quad . . (7)$$

Where: r = capillary radius in cm.
L = capillary length in cm.
V = Volume of flow in cm.^{3}
t = time of flow in sec.
P = pressure causing flow in gms/cm.^{2}
ρ = density in gms./cm.^{3}
λ = a constant, generally = 1.12.

m = "Couette correction" to length

For long capillaries, streamline flow, and velocities where kinetic energy correction may be neglected:

$$\text{Pressure} = \frac{1.82}{10^6} L r \rho\ (\text{Avg. Shear rate})\ (\text{viscosity}) \quad . . (8)$$

where: pressure causing flow is in lbs./sq. inch, viscosity is in cs

$$\text{Shear rate, avg.} = \frac{2v}{\pi r^3} = \frac{Q}{4.9 r^5} \quad . . (9)$$

v = flow rate in cm/sec, and Q = volume flow in cm^3/sec.

If flow is by gravity:

$$Cs = \frac{38{,}500 r^4 h t}{VL} - \frac{4.47 V}{tL} \quad . . (10)$$

where: h = height in cm

For a given instrument, this is equivalent to equation (11).

*Bureau of Standards, Scientific Paper #298, p. 65.

†The flow of oil is accomplished by a gravity head of 12.50 cm at the start, and 2.22 cm at the time 60 cc have been measured in the flask under the tube, giving an average head of 7.36 cm. The orifice is 0.177 cm diameter (0.070") and 1.225 cm long (0.483"), having a ratio of length to diameter of a little less than 7. (Bureau of Stds. Tech. Paper #112. p. 7.)

Courtesy The Emil Greiner Co.

Figure 10 — A typical constant temperature water bath for four Saybolt tubes. Electric heaters, a stirrer and thermostat assure uniform temperature.

and finally checking with two or three standardized oils of different viscosities.

The equation for the Saybolt viscometer as obtained from its designed dimensions has been calculated to be:[8]

$$\text{Kinematic Vis. (Cs)} = 0.22\,t - \frac{180}{t} \quad ..\ddagger\ddagger(12)$$

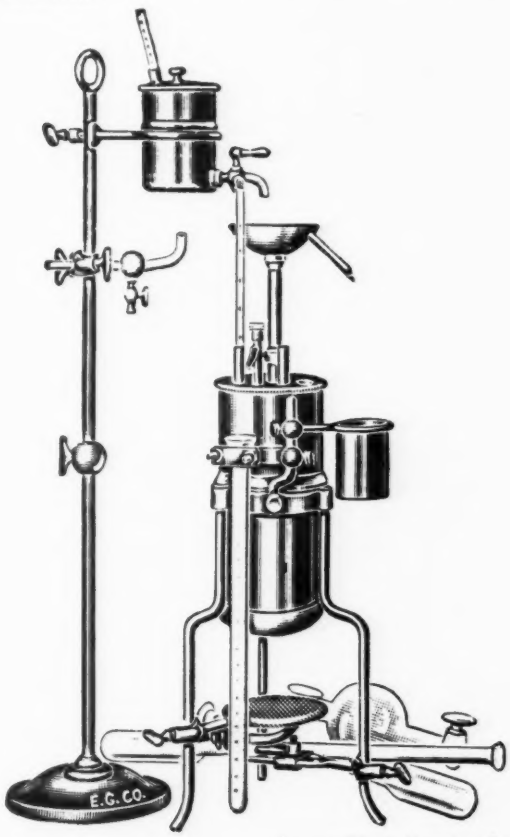
This relationship may be expressed graphically on a chart such as Figure 12, which was published in "Lubrication" in April 1945, and was a revision of the similar chart developed by MacCoull and first published in "Lubrication" in May 1921. The revisions covered only the position of the Barbey line. These curves for all instruments shown were determined from carefully run tests on typical commercial instruments, with a series of liquids of known viscosity. Besides their use as a simple means of converting the readings obtained by these instruments into kinematic units, they have proven very useful in converting readings from one viscometer to another.

Several characteristics of the different instruments indicated on Figure 12 should be mentioned here to explain the nature of these curves:

1. The Saybolt Furol is a modification of the standard Saybolt for testing high viscosity petroleum oils such as bunker fuels, with the orifice enlarged to 0.317 cm. It was the intention to have 10 times the flow rate and thus one-tenth the time of reading. The relation will be seen to approximate this intended value.

2. A similar condition exists between the standard Redwood instrument and the Redwood Admiralty.

3. Many commercial viscosity values taken on the Engler are expressed in terms of "degrees Engler", in which the efflux time of an oil under test is divided by the efflux time of water at 20°C. in the same instrument. The purpose is to reduce the differences in readings on different Engler instruments due to dimensional inaccuracies. This does not give a "specific viscosity" scale, which would be relative to the viscosity of water, because of the curvature of the conversion curve at low viscosities.



Courtesy The Emil Greiner Co.

Figure 11 — Barbey "Ixometer". Flow rate is determined by time required for a given volume at a fixed head. Because of a long flow tube restricted by a steel rod along its axis the flow rate is directly proportional to kinematic viscosity, from water to any higher viscosity.

††Experience has indicated that these instruments as delivered are more satisfactorily represented by two different equations — one for efflux time below 100 seconds, and the other above 100 seconds.[9]
Tables are available for standardized conversions from Saybolt to Kinematic Viscosity. (ASTM designation: D446-39.)

[8]Bureau of Standards Tech. Paper #112, p. 19.

[9]API Proc., Div. of Refining, June 1932, p. 56.

4. The Barbey "Ixometer" shown in Figure 11 consists of a brass tube 5 mm in diameter and 20 cm long, containing a central rod 4 mm in diameter. Readings are reported as the oil flow rate in cc per hour, under a *constant gravity head* maintained by an overflow cup (though the actual readings consist of the number of cc of oil which flow in 10 minutes). Since the flow rate is expressed in volume per unit of time ("fluidity") instead of the inverse, time per unit of volume, the conversion curve shown in Figure 12 slopes in the opposite direction from the other curves. Note that this is the only one of these instruments having a straight line relation between its readings and the kinematic viscosity of a liquid, over a range from water up. It would therefore appear that this might have the unique characteristic of a single calibration with water only (viscosity = 1 cp). However, the manufacturer has objected to the use of water because of the possibility of corrosion of the internal steel rod. Each instrument when manufactured is adjusted by alteration of the height of the supply cup until a reference sample of rapeseed oil has a flow rate of 100 ml per hour at 35°C. Unfortunately various samples of any vegetable oil, such as rapeseed, vary with source and age so that different units which have been supplied by the manufacturer vary from each other, and there is some uncertainty as to what is a standard instrument. From tests on a number of these instruments in the United States, it appears that they should follow the equation:

$$\text{Kinematic Vis.} = \frac{5200}{\text{cc/hr}} \qquad \ldots (13)$$

which is the value indicated in the revised conversion chart shown in Figure 12.

All the viscometers represented in Figure 12 have a straight line relation with kinematic viscosity above some limiting viscosity; about 50 cp except for the Saybolt Furol. Below this viscosity, the lines curve

DIRECTIONS FOR USE OF CHART

OBJECT: To find the viscosity reading of a particular oil on any of the standard viscometers when its reading on one of the viscometers has been determined by experiment *at the same temperature*.

SCALES: There are two sets of scales which *must not be confused* with each other.

X: The scales at bottom and left hand side go together. They are the ones regularly used in practice applying to all ordinary oils.

Y: The scales at top and on right hand side go together. They are rarely used, applying only to very viscous products beyond the range of the other scales.

NOTE: There are two lines of scales at the bottom:

(a) The *lower* scale applies only to *degrees*-Engler.

(b) The *upper* scale applies to all other readings, including Engler-*time*.

In simply changing from one viscometer to another the scales at left and right are not used.

The scales at top must never be used in connection with those at the bottom.

APPLICATION OF CHARTS: X: For ordinary cases.

GIVEN: Saybolt Universal Viscosity = 120″.

DESIRED: Case (a) equivalent Barbey reading.
Case (b) equivalent Engler-degree reading.

PROCEDURE: Find point on bottom scales for Saybolt Universal corresponding to 120″ (A).

Follow up vertically to curve marked Saybolt Universal (the known instrument) (B).

(a) To get Barbey reading: Follow horizontally to curve marked Barbey (C).
Drop down to bottom scale for Barbey and read (D). Reading = 208°.

(b) To get Engler-Degree reading: Follow horizontally to curve marked Degrees-Engler (E).
Drop down to *lower* of the two bottom scales, for Engler-Degrees and read (F). Reading = 3.60°.
i.e., 120″ Saybolt = Barbey 208° = Engler 3.60°.

Y: For very viscous fluids beyond range of other scales.

GIVEN: Engler-Degrees = 1100°.

DESIRED: Equivalent Saybolt Furol reading.

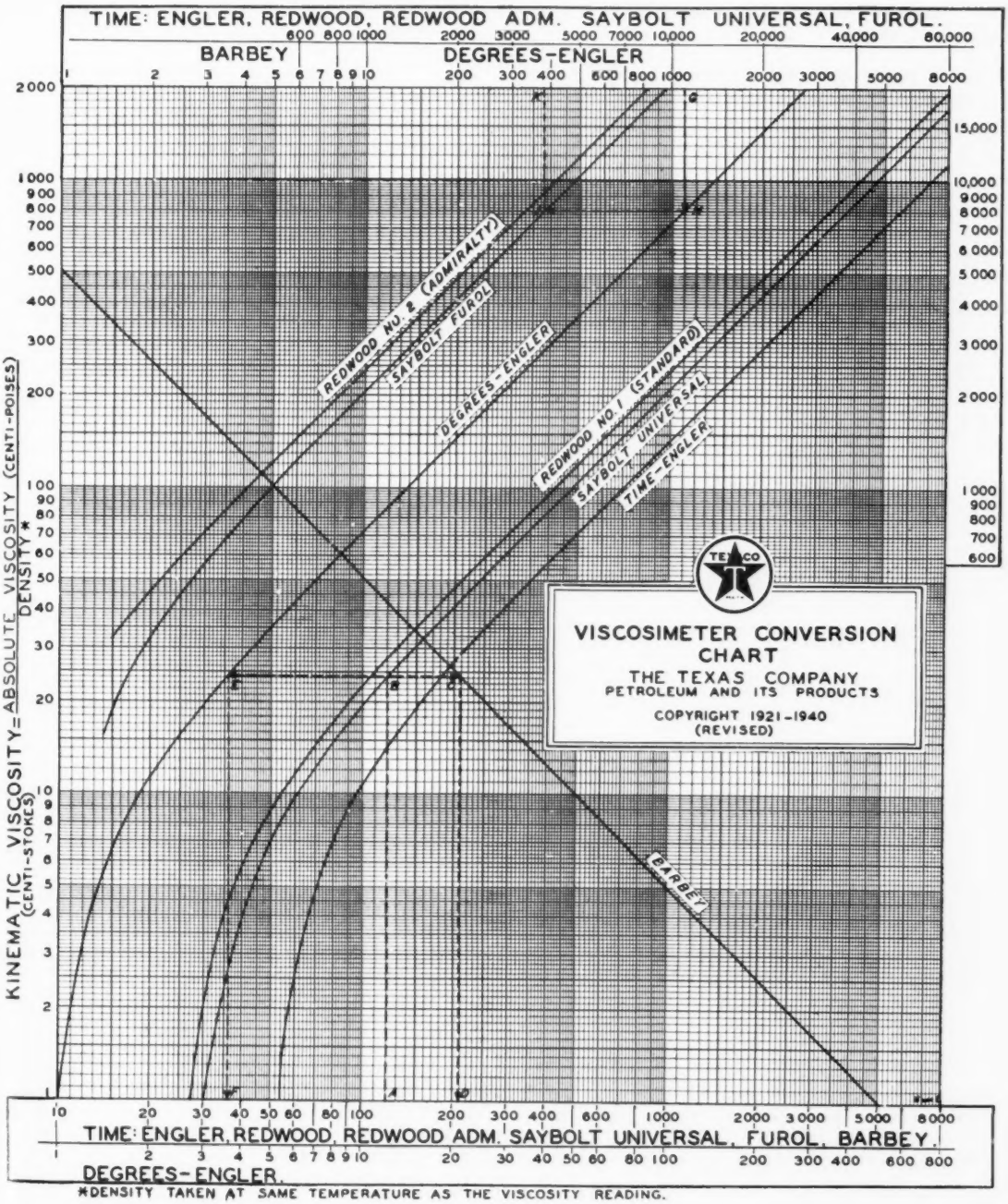
PROCEDURE: Find point on upper scales under Degrees-Engler Corresponding to 1100° (G).

Follow vertically down to Degrees-Engler curve (H).

Follow horizontally to curve marked Furol (J).

Rise vertically to scales under Furol and read (K). Reading = 3800″.

i.e., 1100° Engler = 3800″ Furol.


TIME: ENGLER, REDWOOD, REDWOOD ADM. SAYBOLT UNIVERSAL, FUROL.
BARBEY
DEGREES-ENGLER
KINEMATIC VISCOSITY = ABSOLUTE VISCOSITY (CENTI-POISES) / DENSITY*
(CENTI-STOKES)
REDWOOD NO. 2 (ADMIRALTY)
SAYBOLT FUROL
DEGREES-ENGLER
REDWOOD NO. 1 (STANDARD)
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*DENSITY TAKEN AT SAME TEMPERATURE AS THE VISCOSITY READING.

Figure 12

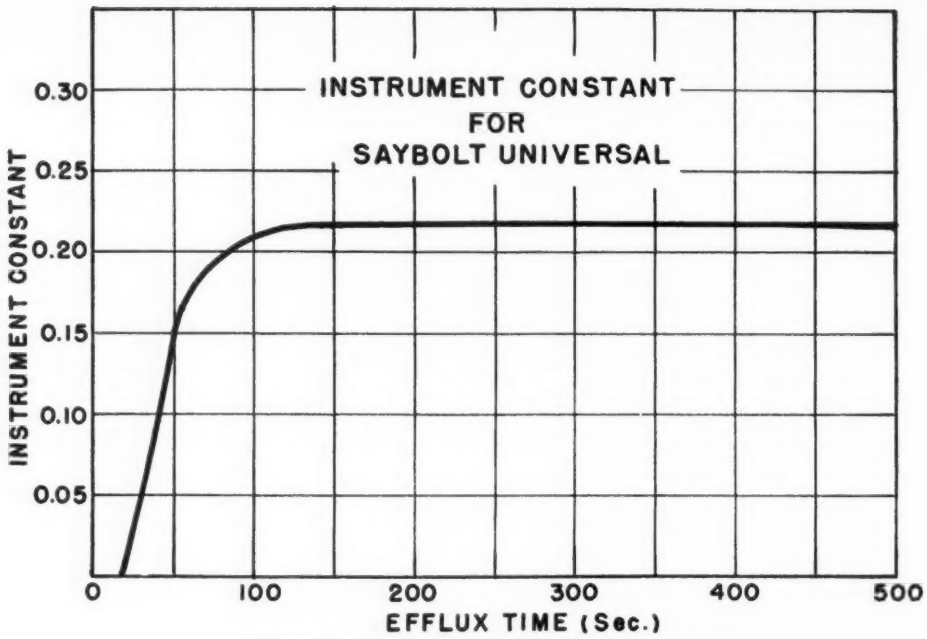


Figure 13 — Instrument constant for Saybolt Universal Viscometer.

downward (except for the Barbey), and become very nearly vertical at 1 cp. This curvature comes in where the time of flow is small enough to make the second term of Equation (11) an increasingly important factor. The reason for this curvature is primarily the fact that an appreciable part of the energy available from the gravity head of the oil, instead of being used up entirely in overcoming the viscous resistance to flow, is expended in kinetic energy by giving velocity to the oil stream. This energy is a function of the velocity squared, and will be small enough to be ignored where the flow rate is restricted to more than 200 seconds on the Saybolt Universal but becomes increasingly important at lower viscosities. For higher viscosities, the following simple relation holds:

. . (14)

Viscosity (Cs) = K × (efflux time),
where K is the instrument constant.

In Figure 13 this constant is plotted against efflux time and clearly indicates the limitations to the use of a single instrument constant for viscosities above 200 seconds. For efflux times above 200 seconds, the constant K is 0.217 for oils at 100°F., and 0.7% lower for oils run at 210°F.[10] This correction is required primarily because of the shrinkage in volume of the stream of hot oil as it cools off in the measuring flask. This results in a slightly greater volume flow through the orifice at high temperature than measured in the receiving flask which is at room temperature.

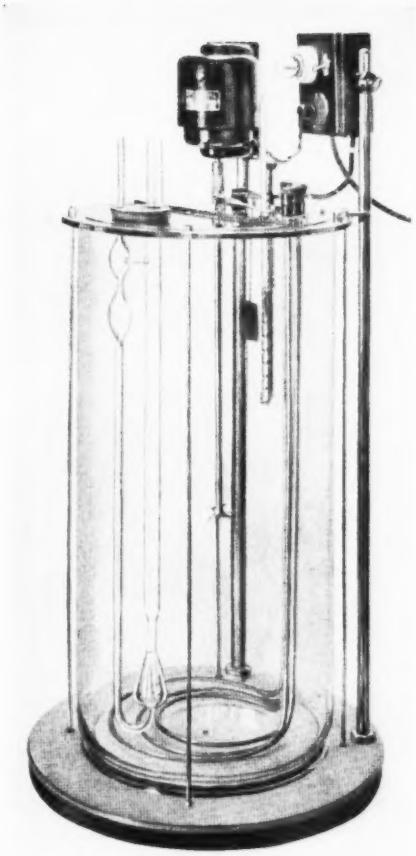
Fundamental Viscosity Measurements

Fundamental measurements of viscosity are calculated by formulae such as equations (7) to (10), from carefully measured dimensions of the capillaries used. Such measurements include not only the average diameters, by weighing the mass of mercury required to fill the tubes, but include complicated corrections for slight deviations of diameter along their length, from measurements by a suitable microscope of the length of a small section of mercury as it is moved from station to station along the bore.[11]

Also, consideration has to be given to a phenomenon connected with the entrance of the fluid into the capillary which increases its effective length. This may be discounted if the tube is so long that the entrance losses make up a negligible percentage of the results. Experimentally, tubes of different lengths are used and when the results are plotted against the tube length it becomes evident how long they must be to disregard these end effects. By such tedious methods, the absolute viscosity of water has been found, which can now be used as a primary standard to calibrate a master viscometer such as that shown in Figure 14, with a capillary tube long enough to neglect entrance effects. When the in-

[10]ASTM Designation D446-39.

[11]"A Monograph of Viscometry," Guy Barr, p. 60.



Courtesy of American Instrument Company

Figure 14 — Fenske "Master" Viscometer and its constant temperature bath. This is a precision long-capillary Viscometer which may be calibrated with water, and used in turn to evaluate oil samples for calibrating Pipette Viscometers such as shown in Figure 15.

strument constant has been found (equation 14) it may be used to calibrate oils which may then be used as secondary standards for the calibration of instruments suitable for routine viscosity readings.

It is now becoming general practice in the petroleum industry to use Fenske or Modified Ostwald Pipettes[12] such as shown in Figure 15 for routine evaluations. A series of tubes is generally used having capillaries of various diameters for use with oils of different viscosities. A pipette is charged by inverting with the smaller tube (2) immersed in the oil to be tested, and then by means of a suction tube attached to the larger tube (1), drawing in oil to just above the line marked between the second bulb and the capillary section. It is then turned right side up and immersed in a constant temperature bath such as shown in Figure 16. After allowing enough time to assure that the oil has reached the bath temperature, the oil is drawn up to the bottom of the upper bulb by a suction tube, which is then disconnected, allowing the oil to flow by gravity down through the capillary. Time is measured for the meniscus to pass between the two etched lines. Check readings may be taken on the same oil without removing the pipette. The elapsed time is then converted into kinematic viscosity by multiplying by the instrument constant of the particular pipette used.

The original calibration for any pipette is based on the fact that it is used only in the range where the following equation holds:

$$K = \frac{\text{centistokes}}{\text{efflux time}} \qquad \ldots (15)$$

The constant K may obviously be determined by running one or more oils of known viscosity, calibrated on some instrument such as the Master Viscometer shown in Figure 14. To determine the range over which this constant holds, a plot such as Figure 17[13] may be made, which indicates that the pipette tested should not be used for viscosities

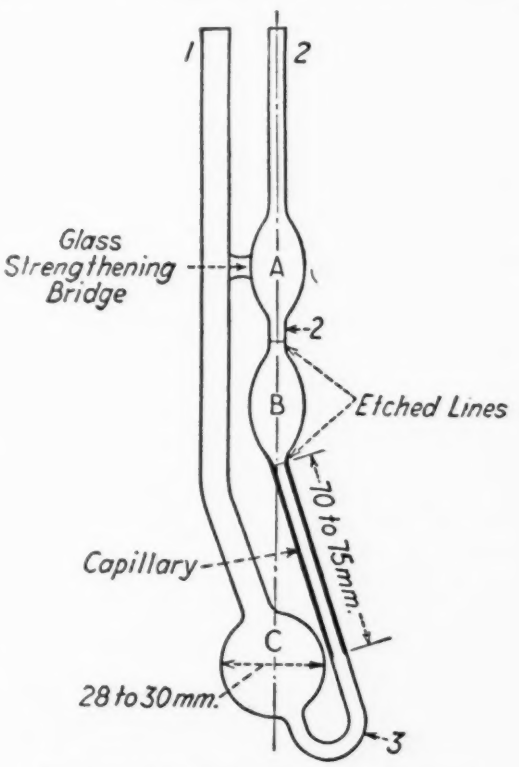
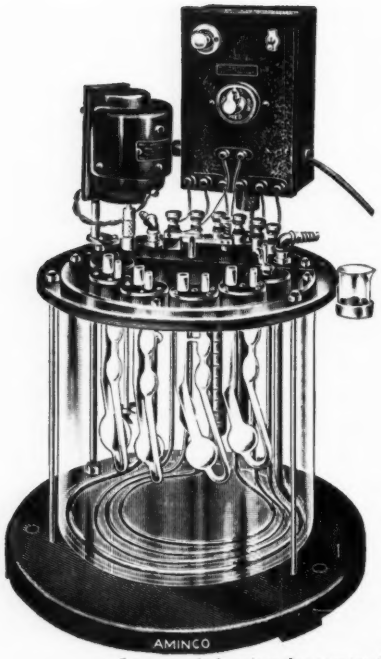


Figure 15 — A.S.T.M. Modified Ostwald Viscometer.

[12]ASTM Standardized Method No. D445-46T.

[13]Figure 3 of "The Problem of the Viscosity of Lubricants", Fenske & McCluer, API, Proc. Div. of Renning, May 1934, p. 31.



Courtesy of American Instrument Company

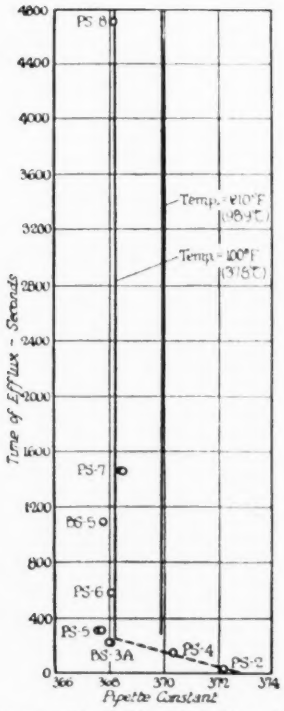
Figure 16 — Constant temperature bath for six Fenske Pipettes. An electric heating coil is shown at the bottom.

which will have an efflux time less than about 400 seconds.

Rate of Shear

In practically all instruments used for the measurement of viscosity (efflux or torsion) the rate of shear between the imaginary layers of a fluid when tested is much lower than often occurs in machines where these fluids are used in commerce. This has been necessitated in order to avoid the instrumental complications which would result if the fluid flow were up in the turbulent* range. It is quite natural that a question should arise as to whether a fluid will have the same viscosity at very high shear rates as at the shear rates where it is customarily measured. This is a difficult question to answer satisfactorily because of the heat generated in the oil film at high shear rates. In even very thin films, the temperatures may be appreciably higher near their center than where they are in contact with their encompassing surfaces.

*See Part III, next issue.



From Figure 3 "The Problem of the Viscosity of Lubricants" by Fenske and McCluer, API Paper, May 24, 1934.

Figure 17 — Instrument constant for a Fenske Pipette. The constant here is the reciprocal of the constant used in the text. Thus:

$$\text{Pipette Constant} = \frac{\text{Efflux Time}}{\text{Kin. Vis.}}$$

A few years ago some experimental data were reported[14] from a special torsion viscometer with slightly tapered cylinder and cup which permitted runs with very thin oil films. The result proved that typical commercial lubricating oils, marketed as motor oils, do not change in viscosity for any shear rate up to the limits tested, which were more than 300,000 as expressed by equation (3) in which the value is spoken of as "reciprocal seconds." There is still some reason to suspect that some special types of oil may lose viscosity at high shear rates, and a forthcoming report of a subcommittee appointed by the API to investigate this matter will be awaited with interest.

[14]ASME Trans. 63 #4 (May 1941), p. 359. "Relationship of Viscosity to Rate of Shear."

THIS ARTICLE WILL BE CONCLUDED IN THE JUNE ISSUE.

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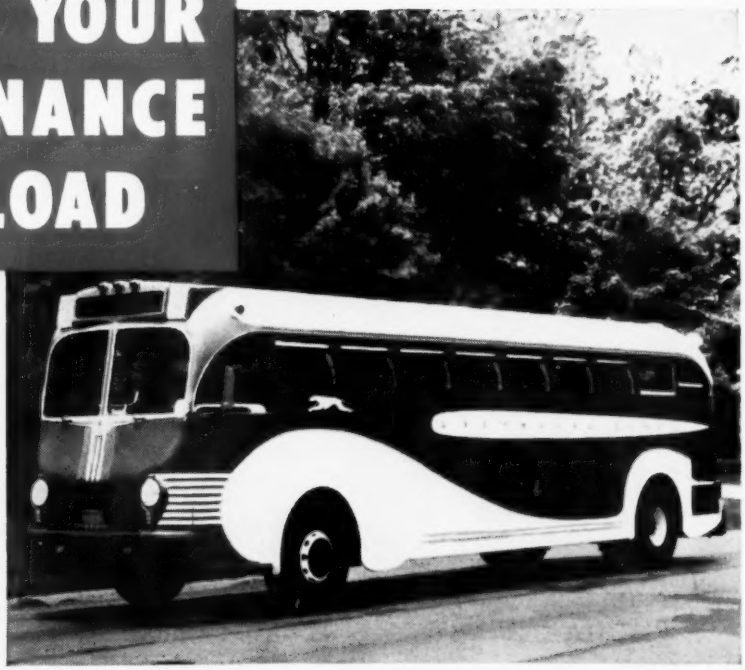

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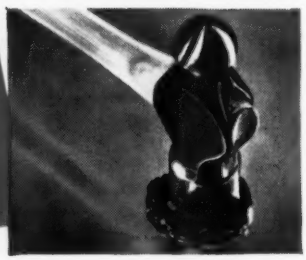

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